U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# CALiPER

## Application Summary Report 20:

LED PAR38 Lamps

November 2012

**Prepared for:**

**Solid-State Lighting Program**
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# 1 Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08[1]) conducted by accredited, independent laboratories.[2] Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.[3]

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Starting in 2012, each CALiPER summary report focuses on a single product type or application. Products are selected with the intent of capturing the current state of the market—a cross section ranging from expected low to high performing products with the bulk characterizing the average of the range. The selection does not represent a statistical sample of all available products. To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,[4] ENERGY STAR® performance criteria,[5] technical requirements for the DesignLights™ Consortium (DLC) Qualified Products List (QPL),[6] or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, LM-79-08 testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warranty, compatibility, and many other facets should also be considered carefully.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

[1] IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit http://www.iesna.org/.
[2] CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP).
[3] CALiPER summary reports are available at http://www.ssl.energy.gov/reports.html. Detailed test reports for individual products can be obtained from http://www.ssl.energy.gov/search.html.
[4] LED Lighting Facts is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see http://www.lightingfacts.com.
[5] ENERGY STAR is a federal program promoting energy efficiency. For more information, visit http://www.energystar.gov.
[6] The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate program eligibility. For more information, visit http://www.designlights.org/.

# 2 Report Summary

This report analyzes the independently tested photometric performance of 38 LED PAR38 lamps. The test results indicate substantial improvement versus earlier CALiPER testing of similar products, and performance comparable to recent data from LED Lighting Facts and ENERGY STAR. Additional testing that focuses on performance attributes beyond those covered by LM-79-08 is planned for this group of lamps, and will be presented in subsequent reports.

Many of the LED lamps tested could be effective replacements for conventional directional lamps in the right application. The lumen output of many of the products was equivalent to 40 to 90 W halogen PAR38 lamps, and all emitted between 388 and 1,363 lumens. Efficacy ranged from 26 to 79 lm/W, although all except one of the products was between 44 and 79 lm/W. The LED PAR38 lamps had luminous intensity distributions ranging from narrow (8° beam angle) to very wide (64° beam angle); the suitability of these distributions depends on the application, but the availability of narrow distributions is an important finding. Although there were a few exceptions, most of the lamps had color quality attributes that were appropriate for replacing halogen PAR lamps in most applications. In an improvement compared to earlier testing, 37 of the 38 products had a power factor higher than 0.70.

All of the LED PAR38 lamps tested offer substantial energy savings compared to halogen PAR38 lamps, and some are more efficacious than compact fluorescent or ceramic metal halide versions. LED products that cover the full range of conventional PAR38 beam angles and that have appropriate color quality, lumen output, and center beam intensity are available. Thus, it is reasonable to conclude that LED PAR38 lamps are (at least in terms of performance) a viable option in most installations where PAR38 lamps are used, although not all lamps can work in all applications (e.g., exterior lighting). Continued expansion of the options available within specific product families would be beneficial, and LED lamps with higher lumen output may be necessary for specialty applications. Lower prices, as well as continued improvements in efficacy, will reduce life-cycle cost and make LED PAR38 lamps more financially attractive.

# 3 Background

Directional lamps—sometimes referred to as reflector lamps—are an essential tool for both ambient and accent lighting, especially in residential and light commercial applications. Directional lamps come in many different shapes, including R (reflector), BR (bulged reflector), ER (elliptical reflector), and PAR (parabolic aluminized reflector), among other specialized forms. This family of lamps shares the attribute of having directional emission, with the different designations helping to indicate the material, shape, and optical system.

Importantly, R, BR, and ER lamps are formed from blown glass, whereas PAR lamps combine a pressed glass lens with a separate reflector, allowing for more precise optical control. Thus, a greater proportion of PAR lamps are used in demanding applications, such as museum, retail, hospitality, and landscape lighting. PAR lamps—and directional lamps in general—are commonly installed in track heads or downlights, and offer great flexibility because of the variety of available lumen packages and beam characteristics. There are no rigid performance criteria to delineate PAR, R, BR, and ER lamps, although generalized characterizations are possible. For example, conventional PAR lamps tend to have narrower luminous intensity distributions and higher efficacies than BR- or R-shaped lamps.

All reflector lamps originally utilized incandescent filaments, which when uncontrolled are characterized as omnidirectional point sources. Reflector lamps were designed to control light using reflectors and/or lenses, resulting in a directional emission that is beneficial for many applications. Currently available halogen PAR lamps utilize a single-ended, quartz filament capsule positioned at the center of a parabolic reflector, which redirects light in parallel rays. The capsule is typically filled with halogen, a gas that can increase efficacy and reduces tungsten evaporation to extend lamp life. The capsule may also incorporate a special coating that reflects infrared radiation back onto the filament, which can increase efficacy; this technology is known as halogen infrared (HIR). Lamps with alternative source types—such as compact fluorescent (CFL), ceramic metal halide (CMH), or LED—may replicate the overall form factor defined by the American National Standards Institute (ANSI), but may have other limitations. The different operating characteristics of CFL and CMH lamps (e.g., warm-up and restrike time, limited sizes, poor dimming performance, etc.) may make them less suitable for meeting the performance requirements in applications where dimming is needed, a variety of beam angles and intensities is desired, or frequent switching is expected.

LEDs are inherently directional, which makes them well suited for use in lamps intended to replace conventional reflector lamps. Additionally, the optics can be arranged at the LED package level, reducing the need for reflectors and lenses that shape the beam (e.g., integrated LED lamps typically do not use parabolic aluminized reflectors). However, because they do not use the same optical system as conventional lamps, the lamp designation can be ambiguous. In other words, it is less clear when an LED lamp should be called a PAR lamp, BR lamp, R lamp or something altogether different. Some LED lamps that perform similarly to PAR lamps are identified as BR or R lamps by the manufacturer, and some LED lamps that perform similarly to BR or R lamps are called PAR lamps. Sometimes a manufacturer will designate the lamp type based on bulb appearance alone, irrespective of photometric performance.

## Definition and Physical Characteristics

The nomenclature for lamps is defined by the American National Standard Lighting Group (ANSLG) in document ANSI C79.1-2002. The first letter(s) used in a lamp designation identifies the shape classification of the bulb. The PAR designation—generally meaning *parabolic aluminized reflector* despite the fact that other materials besides aluminum may be used—is defined to indicate, “A bulb formed by the sealing together during the lamp-making process of a pressed glass parabolic section and a pressed glass lens." Similarly, the IES Lighting Handbook gives the definition: "An incandescent filament or electric discharge lamp in which the outer bulb is formed of two pressed parts that are fused or sealed together; namely a reflectorized bowl and a cover that may be clear or patterned for optical control." In addition to the shape designation, the number symbol indicates the nominal diameter of the bulb in eighths of an inch. For example, a PAR38 lamp has a nominal diameter of 38 eighths of an inch, or 4.75 inches. Almost all PAR38 lamps have a medium (E26) screw base.

Separately, ANSI C78.21-2003 defines standard lamp classes for PAR, R, BR, and ER lamps; PAR38 designated lamps must meet the dimensions provided in Figure C78.21-238. Accordingly, they must have an overall length between 5.0625 inches and 5.3125 inches, and a maximum diameter of 5.3125 inches, among other dimensional tolerances. There is no minimum diameter specified.

## Classifying the Distribution of Directional Lamps

Directional lamps are commonly specified based on their luminous intensity distribution. Figure 1 illustrates the relationship between three descriptors of distribution: center beam candlepower (CBCP), beam angle, and field angle. Complete descriptions of these terms, among others, are included in Appendix A. Of these, beam angle is the most widely cited value in manufacturer literature and on product packaging. ANSI recommends the following system for identifying the nominal beam angle of PAR lamps:

- For beam angles of less than 13°, the angle rounded to the nearest whole number should be used: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12.
- For beam angles of 13° to 50°, the angle rounded to the nearest 5 should be used: 15, 20, 25, 30, 35, 40, 45, and 50.
- For beam angles of 51° or greater, the angle rounded to the nearest ten should be used: 50, 60, 70, 80, and 90.

Numerical designations are often augmented (or replaced) by written characterizations, although these can be nebulous. *Spot* lamps typically have a nominal beam angle of 20° or less, whereas *flood* lamps typically have a nominal beam angle of 25° or more, but there is no accepted standard for further numerical sub-classification. Common terms include very narrow spot (VNSP), narrow spot (NSP), spot (SP), wide spot (WSP), narrow flood (NFL), flood (FL), or wide flood (WFL), but there is no industry standard defining these descriptors in terms of beam angle, and there is sometimes overlap in the categories across different manufacturers. ANSI C78.379-2006 recommends that distributions are denoted with both the descriptor and the beam angle, which allows the numerical designations to be compared (e.g., FL40 for a flood lamp with a 40° beam angle, or NSP9 for a narrow spot with a 9° beam angle).

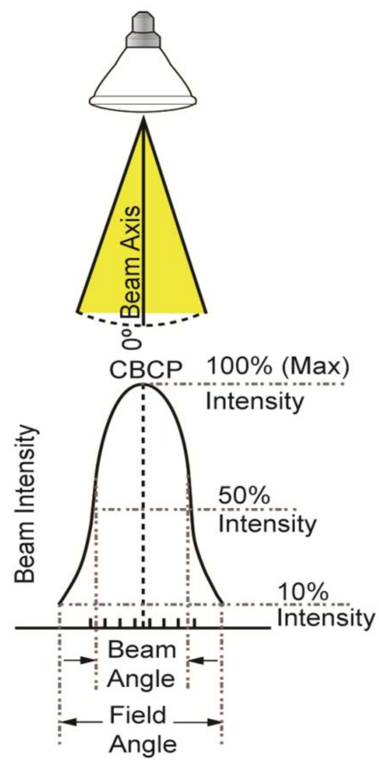



**Figure 1. Describing and quantifying the distribution of directional lamps.** According to the Illuminating Engineering Society (IES), beam angle is the point at which the luminous intensity is 50% of its greatest value. Field angle is the point at which the luminous intensity is 10% of its greatest value.

Because of variability in the manufacturing process, beam angles are assigned a tolerance that varies based on the nominal value:

- For a nominal beam angle of 1° to 12°, the tolerance is ±3°.
- For a nominal beam angle of 15°, the tolerance is ±4°.

- For a nominal beam angle of 20° to 40°, the tolerance is ±6°.
- For a nominal beam angle of 45° or higher, the tolerance is ±10°.

Although these tolerances are necessary, they can lead to some ambiguity. For example, the 25° lamp classification can include lamps having an actual beam angle between 19° and 31°. Thus, an accurately classified lamp with a measured beam angle of 19° may have been nominally classified as having either a 20° or 25° beam angle, making it either a spot or a flood lamp. Beyond this systematic quandary, lamps having the same numerical classification can produce patterns of light that appear substantially different. In order to prevent ambiguity, CALiPER does not convert measured beam angles to nominal beam angles.

## Regulations

Beginning with The Energy Policy Act of 1992 (EPAct 1992), the U.S. Government—specifically DOE—has required directional lamps to meet certain luminous efficacy requirements. EPAct 1992 set the minimum efficacy of some PAR and R lamps, whereas all ER and BR lamps—which at that time were considered niche products with small market share—were excluded. Specifically, the requirements applied to PAR and R lamps with diameters greater than 2.75 inches, having a medium base, and operating near line voltage. The legislation set minimum efficacy levels for wattage bins starting with 40–50 W (10.5 lm/W) and ending with 156–205 W (15.0 lm/W). The Energy Independence and Security Act of 2007 (EISA), extended the 10.5 and 15.0 lm/W EPAct 1992 efficacy requirements to lamps with diameters greater than 2.25 inches (down from 2.75 inches), and removed the exemption for BR and ER lamps. In 2009, DOE published a final rule (74 FR 34080), which set efficacy values that account for differences in rated input power, emission spectrum, lamp diameter, and voltage. The regulation applies to all lamps manufactured on or after June 30, 2012. The formulaic approach results in a range of minimum lamp efficacies, from 14.2 to 22.9 lm/W. Some halogen lamps that meet these requirements are currently available, but the regulation represents a unique opportunity and challenge for directional LED lamps to fill the void, competing with other energy efficient alternatives such as CFL and metal halide.

## Installed Base

As of January 2012, DOE estimated that PAR38 lamps made up approximately 17% of the installed base of PAR, BR, and R lamps, which corresponds to approximately 89.7 million units.[7] Approximately 68% of the products were estimated to be installed in residential buildings. Combined, PAR20, PAR30, and PAR38 halogen lamps represent about 38% of the total installed base of PAR, R, and BR shaped lamps. Despite having superior optics, the market share is likely limited because PAR lamps cost significantly more than BR and R shaped lamps. The minimum efficacy of BR shaped lamps was not regulated until more recently, allowing these less expensive incandescent lamps to be used in many applications.

## PAR38 Lamps

The PAR38 lamp type was chosen by CALiPER because it is the most common size of PAR lamp, and represents an important category for LED technology. The effectiveness and utility of conventional halogen PAR lamps present a challenge for LED lamps in gaining market share; additionally, PAR38 lamps are used in demanding applications where color quality and visual appearance are important considerations. Although LED PAR38 lamps are making significant strides in matching (and surpassing) the performance of halogen PAR38 lamps across many attributes, there is still room for improvement. This makes PAR38s a valuable testing ground for in-depth analysis. Beyond this report, the CALiPER program intends to conduct additional testing on PAR38 lamps,

[7] U.S. Department of Energy. 2012. *Energy Savings Potential of Solid-State Lighting in Niche Lighting Applications*. Solid-State Lighting Program. Available at: http://www1.eere.energy.gov/buildings/ssl/tech_reports.html.

examining characteristics such as lumen maintenance, robustness, color maintenance, and subjective quality issues. This suite of testing will complement the DOE L Prize® PAR38 competition, which was recently reopened.

# 4 Results

## CALiPER LED PAR38 Test Data

### Series 20 LED Lamps

This report analyzes the independently tested performance of 38 LED products designated as PAR38 lamps, which were anonymously purchased in April, May, or June 2012. In this report, they are referred to as the Series 20 products. For more on the product selection parameters, both in general and as they pertain to this group of products, see Appendix B.

All of the units were tested according to IES LM-79-08, using both an integrating sphere and goniophotometer; for each of the Series 20 products, the difference in measured lumen output between the two methods was less than 6%, which is typical. Except for luminous intensity distribution characteristics, all values included in this report were measured using the integrating sphere method. All reported values are the mean of the two samples that were tested; the exception is $D_{uv}$, which is reported as the value furthest from zero. Table 1 summarizes key results from CALiPER testing. Distribution characteristics are provided in the analysis section.

**Table 1. Results of CALiPER tests for the Series 20 LED PAR38 lamps.** Performance criteria include initial output, total input power, luminous efficacy, power factor, color rendering index (CRI), special color rendering index $R_9$, correlated color temperature (CCT), and $D_{uv}$. The *Labels* column indicates whether the product was ENERGY STAR qualified (ES) or listed by LED Lighting Facts (LF).

| DOE CALiPER Test ID | Initial Output (lm) | Total Input Power (W) | Efficacy (lm/W) | Power Factor | CRI | $R_9$ | CCT (K) | $D_{uv}$ [1] | Labels | |
|---|---|---|---|---|---|---|---|---|---|---|
| 12-62 | 977 | 18.4 | 53 | 0.74 | 84 | 42 | 3064 | 0.0003 | ES | LF |
| 12-64 | 1,079 | 17.1 | 63 | 0.89 | 82 | 5 | 3053 | -0.0011 | ES | |
| 12-65 | 1,195 | 24.1 | 50 | 0.75 | 82 | 2 | 2743 | 0.0007 | ES | |
| 12-66 | 471 | 10.6 | 44 | 0.79 | 83 | 28 | 3088 | -0.0062 | ES | |
| 12-67 | 976 | 12.4 | 79 | 0.93 | 96 | 83 | 3016 | 0.0020 | ES | LF |
| 12-72 | 1,150 | 20.1 | 57 | 0.70 | 93 | 59 | 3037 | 0.0010 | ES | LF |
| 12-73 | 721 | 15.0 | 48 | 1.00 | 83 | 19 | 3134 | -0.0039 | | LF |
| 12-74 | 906 | 17.0 | 53 | 0.96 | 84 | 27 | 3338 | 0.0023 | | LF |
| 12-75 | 840 | 16.3 | 52 | 1.00 | 82 | 41 | 2974 | 0.0003 | ES | LF |
| 12-76 | 756 | 12.8 | 59 | 0.95 | 75 | -16 | 6404 | 0.0032 | | LF |
| 12-77 | 1,363 | 17.8 | 77 | 0.74 | 82 | 17 | 3069 | -0.0016 | ES | LF |
| 12-78 | 931 | 18.0 | 52 | 0.77 | 84 | 24 | 3500 | -0.0010 | ES | LF |
| 12-79 | 848 | 17.2 | 49 | 0.94 | 83 | 18 | 2986 | -0.0011 | | |
| 12-80 | 958 | 17.1 | 56 | 0.81 | 84 | 28 | 3082 | -0.0034 | ES | LF |
| 12-81 | 1,018 | 16.1 | 63 | 0.81 | 82 | 12 | 3056 | -0.0006 | | |
| 12-82 | 883 | 14.7 | 60 | 0.98 | 83 | 27 | 3033 | -0.0010 | ES | LF |
| 12-85 | 874 | 19.4 | 45 | 0.94 | 81 | 22 | 2999 | -0.0027 | | |
| 12-86 | 1,088 | 17.8 | 61 | 0.92 | 83 | 16 | 3041 | -0.0005 | | |
| 12-87 | 603 | 10.7 | 57 | 0.78 | 83 | 29 | 3166 | -0.0020 | ES | LF |

**(continued on next page)**

1. Red values are outside of ANSI-defined limits (ANSI C78.377).

**Table 1. (continued)**

| DOE CALiPER Test ID | Initial Output (lm) | Total Input Power (W) | Luminous Efficacy (lm/W) | Power Factor | CRI | $R_9$ | CCT (K) | $D_{uv}$ | Labels | |
|---|---|---|---|---|---|---|---|---|---|---|
| 12-88 | 745 | 12.0 | 62 | 0.93 | 79 | 7 | 2761 | 0.0015 | | LF |
| 12-89 | 661 | 13.8 | 48 | 0.53 | 82 | 23 | 2752 | 0.0005 | | |
| 12-90 | 932 | 16.6 | 56 | 0.91 | 96 | 77 | 2771 | 0.0001 | ES | LF |
| 12-91 | 1,002 | 17.0 | 59 | 0.75 | 82 | 17 | 3062 | -0.0017 | ES | |
| 12-92 | 1,157 | 16.9 | 68 | 0.99 | 83 | 18 | 3089 | -0.0020 | | LF |
| 12-93 | 769 | 15.9 | 48 | 0.95 | 83 | 39 | 2950 | -0.0012 | | LF |
| 12-94 | 781 | 14.6 | 54 | 0.78 | 83 | 19 | 3017 | -0.0015 | | LF |
| 12-95 | 799 | 16.3 | 49 | 0.98 | 83 | 26 | 3012 | -0.0010 | ES | LF |
| 12-96 | 738 | 14.4 | 51 | 0.98 | 83 | 44 | 2919 | -0.0001 | | LF |
| 12-97 | 710 | 15.6 | 45 | 0.79 | 80 | 22 | 3246 | -0.0034 | | |
| 12-98 | 750 | 29.0 | 26 | 0.92 | 82 | 27 | 3129 | 0.0024 | | |
| 12-99 | 969 | 16.9 | 57 | 0.72 | 82 | 16 | 3079 | 0.0036 | ES | LF |
| 12-100 | 747 | 11.0 | 68 | 0.76 | 82 | 24 | 2995 | -0.0005 | | |
| 12-101 | 749 | 11.1 | 68 | 0.98 | 75 | -19 | 6307 | 0.0046 | | |
| 12-102 | 787 | 13.7 | 57 | 0.94 | 81 | 9 | 2982 | 0.0000 | | |
| 12-103 | 1,338 | 18.2 | 73 | 0.97 | 82 | 9 | 2750 | -0.0003 | | |
| 12-104 | 581 | 10.6 | 55 | 0.77 | 84 | 29 | 3147 | -0.0015 | ES | |
| 12-134 | 829 | 15.6 | 53 | 0.85 | 81 | 13 | 3081 | 0.0006 | ES | |
| 12-135 | 388 | 8.4 | 46 | 0.90 | 81 | 13 | 2742 | -0.0032 | | |
| **Minimum** | 388 | 8.4 | 26 | 0.53 | 75 | -19 | 2742 | - | | |
| **Mean** | 870 | 15.8 | 56 | 0.86 | 83 | 23 | 3199 | - | | |
| **Maximum** | 1,363 | 29.0 | 79 | 1.00 | 96 | 83 | 6404 | - | | |

The Series 20 benchmark products are shown in Figure 2, with the LED products shown in Figure 3. The construction of the lamps varied substantially, with different strategies for thermal management and different quantities of LED packages being the most noticeable. In contrast with the recently tested LED BR30/R30 lamps, most of the LED PAR38 lamps used individual optics for each LED package, rather than a diffusing lens covering the entire emitting area.


**Figure 2. Photographs of five conventional PAR38 lamps (one CFL and four halogen) tested in conjunction with the Series 20 LED products.**


**Figure 3. Photographs of the CALiPER Series 20 LED PAR38 lamps.**

**Past CALiPER Results for LED PAR38 Lamps**

The CALiPER program previously tested eight PAR38 lamps, which were purchased between 2008 and 2010. A summary of key results is available in Appendix C. In general, these products represent earlier iterations of integrated LED lamp technology; as expected, the performance is typically worse than for the Series 20 products. Notably, five of the previously tested products were from manufacturers whose products were tested again for Series 20. Direct comparisons can be misleading because the intended performance for some of the products was different (e.g., spot versus flood distribution, different CCT), but all five of the newer products emitted more lumens than their older counterparts and four of the five products had a higher efficacy. The only product that had lower efficacy also had a lower color temperature. Overall, mean lumen output increased by 46%, whereas input power increased by only 9%. Consequently, mean efficacy increased by 37%.

## Supplemental LED Downlight Data

**ENERGY STAR**

PAR lamps are an important category in the ENERGY STAR program; the pertinent performance criteria from the *ENERGY STAR Program Requirements for Integral LED Lamps* (version 1.4) are provided in Table 2. Other program requirements beyond the scope of LM-79-08 testing conducted by CALiPER are not included. As of October 16, 2012, 879 LED PAR lamps were ENERGY STAR qualified, *although there is no differentiation by lamp diameter*. Thus, more than half of the nearly 1,400 qualified lamps were PAR lamps.

Summary statistics for ENERGY STAR qualified PAR lamps are provided in Table 3. Notably, because lamp diameter is not explicitly listed by ENERGY STAR, this data does not correspond exactly to the CALiPER Series 20 results or LED Lighting Facts data.

**LED Lighting Facts Data**

As of October 16, 2012, LED Lighting Facts listed 440 PAR38 or R38 lamps, grouped in a single category. Given that PAR lamps are a specialized type of reflector lamp with unique performance attributes, this dataset does not necessarily correspond to the CALiPER Series 20 results; in particular, distribution characteristics may be different. However, this assumes LED product manufacturers are accurately labeling products to reflect performance similar to conventional products in the given category. Summary statistics for the PAR38/R38 lamps listed by LED Lighting Facts are provided in Table 4.

## CALiPER Testing of Conventional Product Benchmarks

In conjunction with testing of the Series 20 LED products, five conventional benchmarks were tested, including three 75 W halogen PAR38 lamps, one 60 W HIR PAR38 lamp, and one 23 W CFL PAR38 lamp. These five products supplement two conventional benchmarks from previous testing, including one 130 V, 50 W halogen PAR38 and one 25 W self-ballasted CMH PAR38. Summary data for these seven products is available in Appendix D.

**Table 2.** **Minimum *ENERGY STAR Program Requirements for Integral LED Lamps* (v1.4) criteria relevant to CALiPER testing of LED PAR38 lamps.**

| **CBCP** (cd) | **Efficacy** (lm/W) | **Power Factor** | **Distribution** | **CRI** | **$R_9$** | **CCT** (K) |
|---|---|---|---|---|---|---|
| Determined using tool developed by ENERGY STAR that considers beam angle and input power | 45 (> 2.5" diameter) | 0.70 (> 5 W) | 80% of total initial lumens within a solid angle of π steradians | 80 | 0 | 2700<br>3000<br>3500<br>4000 |

**Table 3.** **Summary data for ENERGY STAR-qualified PAR lamps.** Includes 879 products listed as of October 16, 2012. ENERGY STAR does not differentiate listed products based on lamp diameter.

| | Initial Output (lm) | Total Input Power (W) | Efficacy (lm/W) | CRI | CCT (K) |
|---|---|---|---|---|---|
| **Minimum** | 222 | 4.5 | 39 | - | 2700 |
| **Mean** | 780 | 13.7 | 56 | - | 3022 |
| **Maximum** | 1,350 | 24.5 | 82 | - | 4100 |

**Table 4.** **Summary data for R38/PAR38 lamps listed by LED Lighting Facts.** Includes 440 products listed as of October 16, 2012. LED Lighting Facts does not differentiate between R and PAR lamps.

| | Initial Output (lm) | Total Input Power (W) | Efficacy (lm/W) | CRI | CCT (K) |
|---|---|---|---|---|---|
| **Minimum** | 293 | 6.7 | 34 | 61 | 2641 |
| **Mean** | 874 | 16.0 | 55 | 83 | 3370 |
| **Maximum** | 1,500 | 24.0 | 90 | 95 | 8160 |

The seven benchmark products covered a wide range of output, emitting between 524 and 1,504 lumens. The halogen lamps tested had a mean efficacy of 14 lm/W and the CFL and CMH products both exceeded 50 lm/W. All of the products had a nominal CCT of 2700 K or 3000 K, with the four 120 V halogen lamps all falling between 2842 K and 2887 K—notably, this is the threshold between the 2700 K and 3000 K nominal CCT bins. The halogen lamps all had a CRI just below 100, whereas the CFL and CMH lamps had a CRI in the 80s; this performance is typical of those source types.

The seven benchmarks had a variety of distribution characteristics, with measured beam angles ranging from 10° to 87° and CBCP ranging from less than 500 cd to more than 15,000 cd. Importantly, the limited number of products does not cover the full range of distribution characteristics for a given source type; this is particularly relevant to the halogen and CMH categories. Based on informal reviews of manufacturer literature, halogen and CMH PAR38 lamps are most commonly available in a family with three distribution types, which have beam angles of approximately 9–12°, 25–30°, and 40–50°. CFL PAR38 lamps are typically only available in wide flood distributions, with beam angles exceeding 60°.

# 5 Analysis

## Lumen Output and Efficacy

The Series 20 LED PAR38 lamps had measured output ranging from 388 to 1,363 lumens, with a mean of 870 lumens. In previous CALiPER testing, no LED PAR38 lamps were measured above 959 lumens. This contrast exemplifies a more general trend of increasing lumen output in the LED market. Both the lumen output and efficacy of the Series 20 CALiPER products are representative of the LED Lighting Facts and ENERGY STAR datasets, although the CALiPER dataset is much smaller. Efficacy versus lumen output is shown in Figure 4.

The range in output was similar to the range in output seen in standard 40 W to 90 W halogen PAR38 lamps. Energy efficiency regulations have effectively stopped the production of halogen PAR38 lamps drawing between 100 and 250 W, so the performance range is largely the same for currently available halogen and LED PAR38 lamps. Lumen output is slightly less than the 25 W self-ballasted CMH benchmark. Higher output metal halide lamps—70 to 150 W or more—are also available, although they require dedicated ballasts and igniters. They are generally used in different applications, such as exterior floodlighting or high ceiling applications.

All but two of the Series 20 LED products exceeded 45 lm/W, which is the minimum level for ENERGY STAR qualification. The most efficacious product was measured at 79 lm/W, and the mean efficacy was 56 lm/W. This

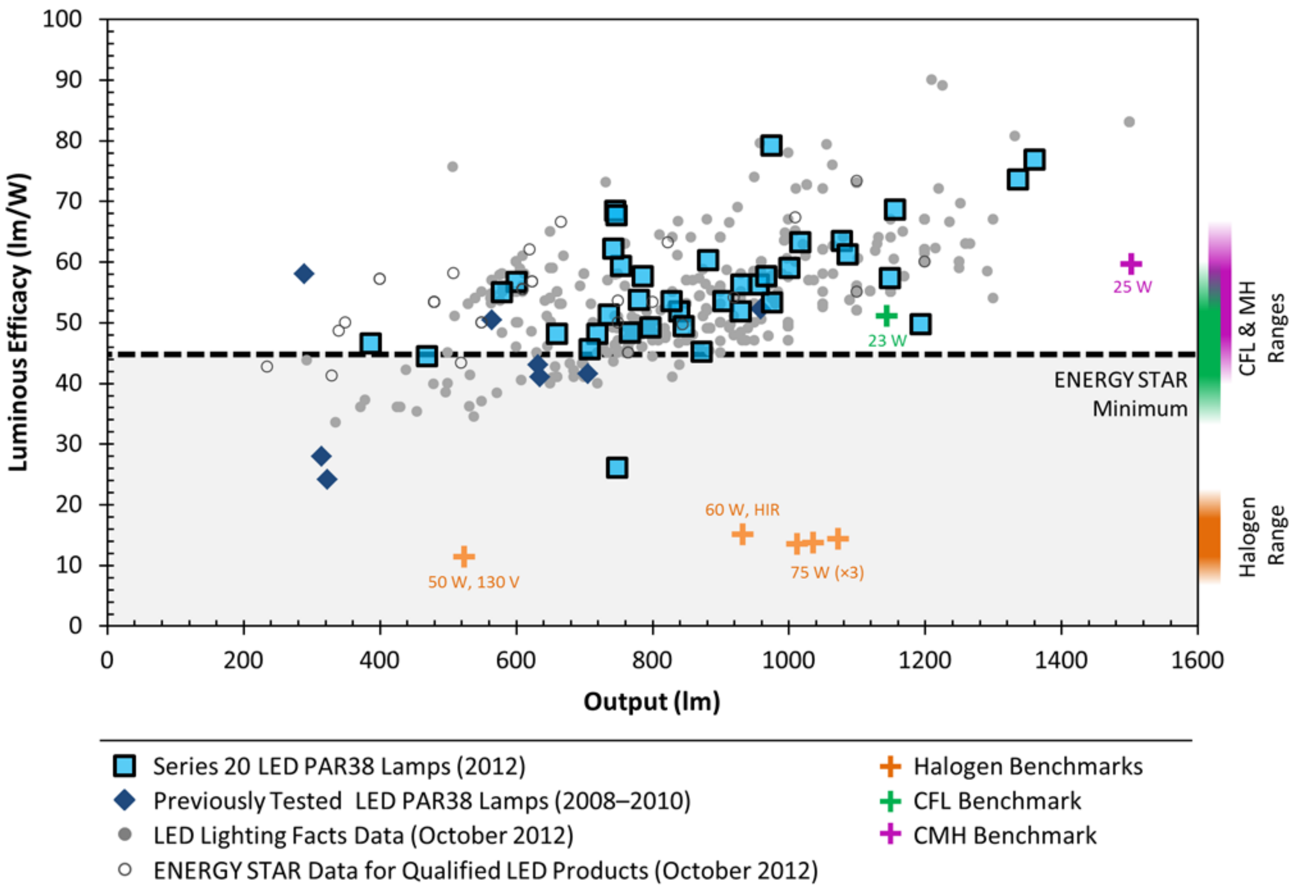



**Figure 4. Luminous efficacy versus lumen output for the Series 20 LED PAR38 lamps compared to other datasets.** The performance range was similar to LED Lighting Facts, and all of LED lamps had higher efficacy than the halogen benchmarks. Efficacy was generally similar to or better than the CFL and self-ballasted CMH benchmarks. The lumen output has increased over time, with many lamps now matching the lumen output of 75 W or 90 W halogen PAR38 lamps.

level of performance is typical of other directional LED lamp types tested by CALiPER (e.g., BR30, AR111). The best products exceeded the efficacy of typical CFL and self-ballasted CMH PAR lamps, and all of the products far exceeded the typical efficacy of halogen PAR lamps.

Of the 38 lamp types tested for Series 20, only eight were available in more than one wattage (or lumen package). This is a notable limitation compared to conventional halogen PAR38 lamps, which are typically available in multiple wattages. As a result, the ability to mix lamps with different outputs in the same space is currently more difficult with LED PAR38 lamps, often requiring products from more than one manufacturer that may or may not match in color appearance. Introducing complete families of products with multiple lumen packages would be beneficial, and would augment existing families of products having multiple CCTs and/or beam angles.

## Distribution of Light

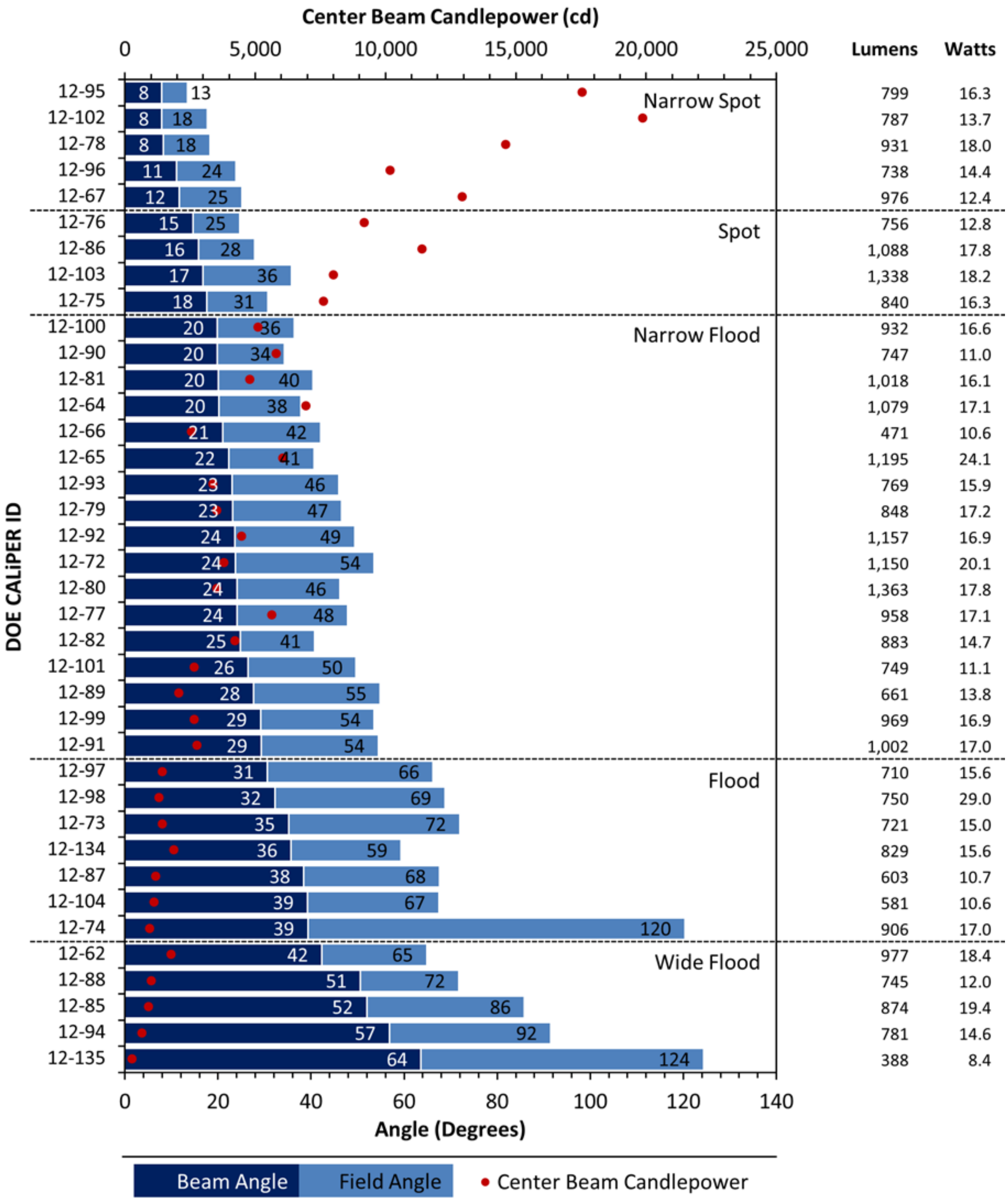
Directional lamps, and especially PAR lamps, are most often specified based on their luminous intensity distribution, which is usually characterized by the beam angle and CBCP (sometimes referred to as center beam intensity). PAR lamps are known for having defined distributions with a more distinct beam, with families of products available in multiple beam angles. This affords specifiers great flexibility in creating a visual composition. At the same time, consumers must be aware of the different available distributions if they are trying to replace an existing lamp with one that performs similarly, or if they are simply trying to choose the right product for an application.

When selecting the Series 20 LED PAR38 lamps, the goal was to include lamps with a broad range of beam angles. As shown in Figure 5, the measured beam angles ranged from 8° to 64°. For this analysis, these lamps have been grouped into five categories based on the measured beam angle: narrow spot (≤ 12°), spot (13°–19°), narrow flood (20°–30°), flood (31°–40°), and wide flood (≥ 41°).[8] Notably, the distribution of beam angles in the selected sample may not be representative of the overall market; however, the prevalence of products in the narrow flood category is likely because this was one of the earliest types of LED PAR38 available. In fact, 29 of the 38 product types examined were available with a narrow flood distribution. In contrast, only seven products were available with a narrow spot distribution, and 12 with a wide flood distribution. Once the wide flood category is reached, there is substantial overlap with BR-shaped lamps, which were examined in *CALiPER Application Summary Report 16*.

In particular, the narrow spot distribution has been sought after by designers, specifiers, and retailers. Conventional PAR lamps are a workhorse in this category, but LED lamps have a greater challenge in providing enough lumens with such a narrow distribution. To provide enough output, LED lamps have generally required more emitting area, which can be achieved with larger LED packages or by aggregating multiple LED packages. Whether using a large LED package and single optical system or multiple LED packages with discrete optical systems, the ratio of emitting area to the optical system is still larger than with halogen lamps. However, as the output of LED packages continues to increase, it is clear—based on available products—that this issue is abating. Several products with narrow spot distributions were included in Series 20.

CBCP is another important aspect of luminous intensity distribution. In some ways, CBCP describes the *punch* that the lamp can provide. As shown in Figure 5, CBCP has an inverse relationship with beam angle; that is; as

[8] Numerical categorizations of terms describing beam angle are not provided by ANSI or any other standards organization. This system was developed by CALiPER for this report and is not intended to establish a precedent.




| ID | Beam Angle | Field Angle | Lumens | Watts |
|---|---|---|---|---|
| 12-95 | 8 | 13 | 799 | 16.3 |
| 12-102 | 8 | 18 | 787 | 13.7 |
| 12-78 | 8 | 18 | 931 | 18.0 |
| 12-96 | 11 | 24 | 738 | 14.4 |
| 12-67 | 12 | 25 | 976 | 12.4 |
| 12-76 | 15 | 25 | 756 | 12.8 |
| 12-86 | 16 | 28 | 1,088 | 17.8 |
| 12-103 | 17 | 36 | 1,338 | 18.2 |
| 12-75 | 18 | 31 | 840 | 16.3 |
| 12-100 | 20 | 36 | 932 | 16.6 |
| 12-90 | 20 | 34 | 747 | 11.0 |
| 12-81 | 20 | 40 | 1,018 | 16.1 |
| 12-64 | 20 | 38 | 1,079 | 17.1 |
| 12-66 | 21 | 42 | 471 | 10.6 |
| 12-65 | 22 | 41 | 1,195 | 24.1 |
| 12-93 | 23 | 46 | 769 | 15.9 |
| 12-79 | 23 | 47 | 848 | 17.2 |
| 12-92 | 24 | 49 | 1,157 | 16.9 |
| 12-72 | 24 | 54 | 1,150 | 20.1 |
| 12-80 | 24 | 46 | 1,363 | 17.8 |
| 12-77 | 24 | 48 | 958 | 17.1 |
| 12-82 | 25 | 41 | 883 | 14.7 |
| 12-101 | 26 | 50 | 749 | 11.1 |
| 12-89 | 28 | 55 | 661 | 13.8 |
| 12-99 | 29 | 54 | 969 | 16.9 |
| 12-91 | 29 | 54 | 1,002 | 17.0 |
| 12-97 | 31 | 66 | 710 | 15.6 |
| 12-98 | 32 | 69 | 750 | 29.0 |
| 12-73 | 35 | 72 | 721 | 15.0 |
| 12-134 | 36 | 59 | 829 | 15.6 |
| 12-87 | 38 | 68 | 603 | 10.7 |
| 12-104 | 39 | 67 | 581 | 10.6 |
| 12-74 | 39 | 120 | 906 | 17.0 |
| 12-62 | 42 | 65 | 977 | 18.4 |
| 12-88 | 51 | 72 | 745 | 12.0 |
| 12-85 | 52 | 86 | 874 | 19.4 |
| 12-94 | 57 | 92 | 781 | 14.6 |
| 12-135 | 64 | 124 | 388 | 8.4 |

**Figure 5. Distribution characteristics of the Series 20 LED PAR38 lamps.** The 38 selected lamps were divided into five categories based on measured beam angle, which ranged from 8° to 64°. The difference in average non-distribution performance characteristics (e.g., lumen output, efficacy, color quality) for the five groups was not substantial.

beam angle increases, CBCP decreases. One concern with LED PAR lamps is that they may not provide the same *punch* as their conventional halogen counterparts. Figure 6 shows CBCP versus beam angle for the Series 20 LED PAR38 lamps, as well as the predicted CBCP from the ENERGY STAR tool used for establishing equivalency—note that the predicted value is not the minimum value used for qualification. Figure 6 also includes a sample of manufacturer-listed values for halogen PAR38 lamps between 60 W and 100 W, the approximate range of

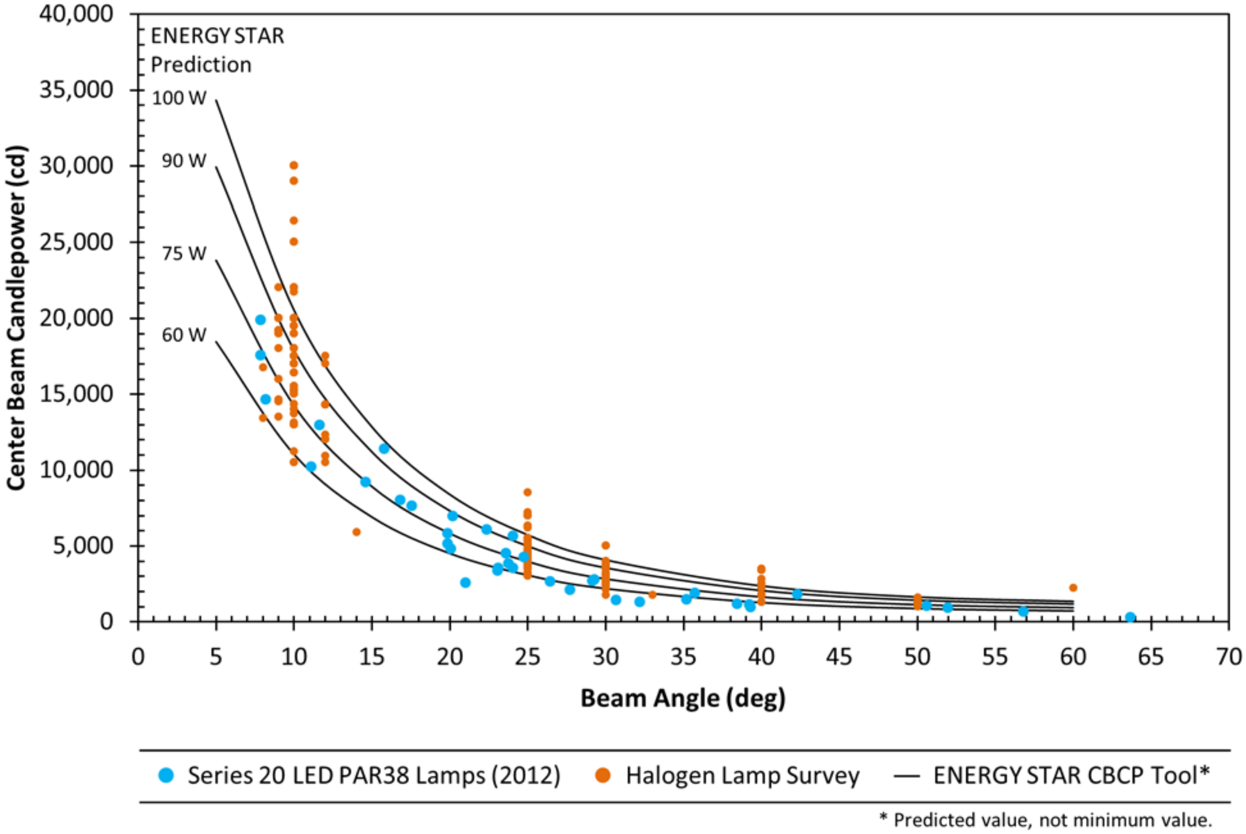



**Figure 6. CBCP versus beam angle for the Series 20 LED PAR38 lamps compared to benchmark data.** Iso-power lines were calculated using the ENERGY STAR CBCP tool; they show the predicted value, not the lower minimum requirement for qualification. The halogen lamp data is from a survey of manufacturer data in the 2008/2009 catalogs of GE, OSRAM SYLVANIA, Philips, and Ushio.

equivalency claims for the Series 20 lamps. Figure 6 demonstrates that the concerns about CBCP may have some merit: at a given beam angle, halogen lamps offer a wider range of CBCPs. Further, for LED products claiming equivalency, halogen lamps with the same beam angle appear to offer higher CBCPs.

Not all aspects of a luminous intensity distribution can be captured numerically using readily available metrics. In some applications, the smoothness of the beam pattern from the center to the edge can be very important. This characteristic lacks a metric, but adjectives such as “smooth,” “spotty,” or “uneven” are sometimes used. This attribute was not analyzed as part of this series of CALiPER testing, although it is intended to be an important aspect of the continued evaluation of the Series 20 LED PAR38 lamps.

## Color Characteristics

Because they are most often used for object lighting in architectural interiors, color quality is an important aspect to consider when evaluating PAR38 lamps. Of particular importance is performance relative to halogen lamps, which are the incumbent technology in this application category. The CCT of the Series 20 LED PAR38 lamps ranged from 2742 K to 6404 K, as shown in Figure 7. More importantly, 35 of the 38 products had a nominal CCT of 2700 K or 3000 K,[9] which matches the two nominal values that bookend typical halogen PAR38 color temperature. Only two products (12-76 and 12-101) did not fall within the range considered acceptable for

[9] Nominal CCT ranges are defined in ANSI C78.377-2008.

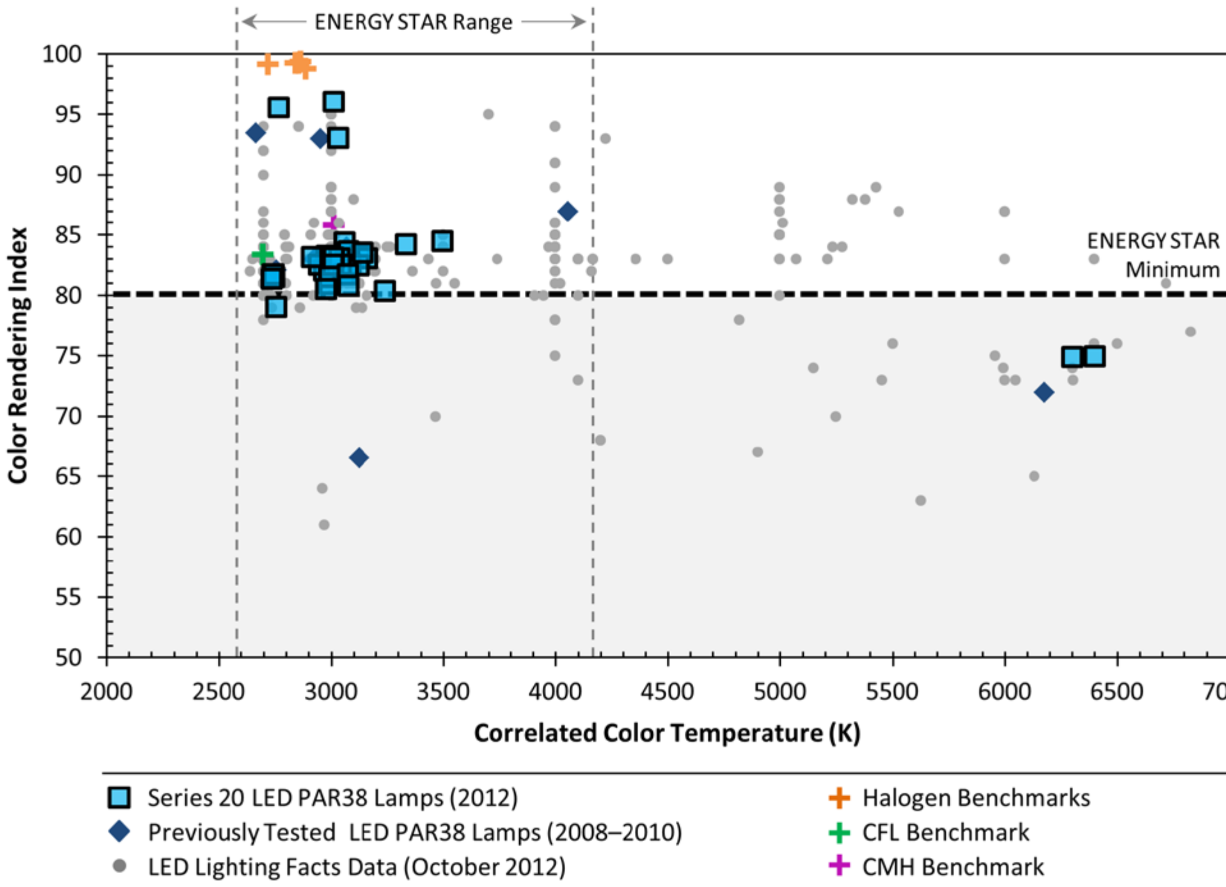



**Figure 7. Color characteristics of the Series 20 LED PAR38 lamps compared to other data.** A vast majority of the Series 20 lamps met the ENERGY STAR criteria, with most lamps having a nominal CCT of 3000 K and a CRI in the low 80s.

ENERGY STAR qualification. Although higher CCTs may be appropriate in some applications, these products may not provide suitable illumination for those seeking a direct replacement for a halogen PAR38 lamp. Only one product (12-66) was measured as exceeding the ANSI range for $D_{uv}$, with a value of -0.0062. The other products had a $D_{uv}$ between -0.0039 and 0.0046, meaning the lamp appearance was neither dramatically more pink nor more green than a lamp whose coordinates fall on the black body locus.

Although most of the Series 20 LED PAR38 lamps had an appropriate nominal CCT, that does not guarantee they can be used side-by-side with halogen or other LED products. There is substantial variability with nominal CCT bins, so noticeable color differences between adjacent lamps of different types is a real possibility. Going a step further, even lamps with the same exact CCT may appear different, owing to differences in $D_{uv}$. This is one reason why having complete families of directional lamps—specifically including multiple lumen packages and beam angles—might benefit LED products. Mixing and matching from different product types may not be an option for exacting applications. Notably, this concern is also present for other energy efficient halogen alternatives, such as CFL and metal halide.

Each of the Series 20 LED products had a CRI between 75 and 96, with a mean for the group of 83. Three products (12-76, 12-88, and 12-101) had a CRI lower than 80, whereas three products (12-67, 12-72, and 12-90) had a CRI greater than 90. The measured CRI for the remaining 32 products was between 80 and 84, which is typical of other directional lamp types tested by CALiPER. It is plausible that the market is settling on this range as an acceptable level for replacement of conventional directional lamps. However, in some applications where directional lamps are a key component (e.g., museums, retail), more exacting color performance may be necessary. As always, in critical applications visual evaluation may be an invaluable tool.

Similar to other recent CALiPER testing, the measured $R_9$ values for the Series 20 LED PAR38 lamps had a strong linear correlation with CRI (r = 0.81). However, for the group or products with a CRI between 80 and 84, the $R_9$ varied between 2 and 44. Given the distorted scale for $R_9$—the color space used in the calculation is distorted in the red region—this difference is roughly equivalent to 10 points on the CRI scale, which is generally considered noticeable.

As with lumen output and efficacy characteristics, the Series 20 LED products had color characteristics similar to the products listed by LED Lighting Facts: a tight cluster with CCTs around 3000 K and CRIs in the low 80s.

## Electrical Characteristics

The input power for the Series 20 products ranged from 8.4 to 29.0 W, with 35 of the products between 10.6 and 20.1 W. The measured power factors ranged from 0.53 to 1.00, with a mean of 0.86. All but one of the LED products had a power factor exceeding the ENERGY STAR minimum of 0.70. This is a substantial improvement over earlier CALiPER results in which four of eight products had a power factor less than 0.70, as shown in Figure 8. CALiPER has made similar observations for several recently tested product types.

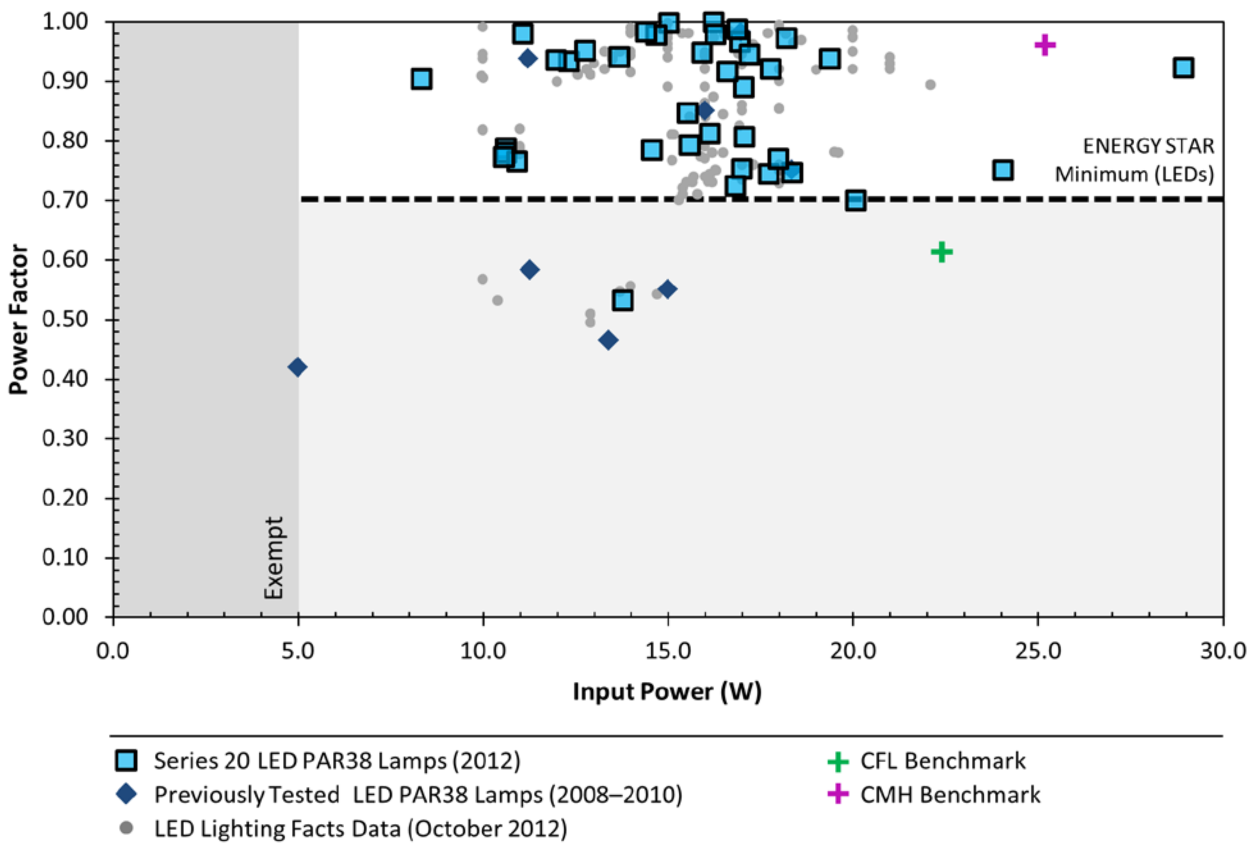



**Figure 8. Power factor versus input power for the Series 20 LED PAR38 lamps compared to other data.** The current products had substantially higher power factors than many previously-tested LED PAR38 lamps. All but one product met the ENERGY STAR criterion of 0.70, and many had a power factor above 0.90.

## Size and Shape

As with other directional lamps, ANSI defines size tolerances for all lamps carrying the PAR38 designation. Although the dimensional tolerances listed by ANSI are more detailed, length and diameter are two that are easily measured. All of the Series 20 products met the diameter requirement (maximum 5.3125 inches), but half of the products were outside the acceptable range for length. Six of the products were too long (more than 5.3125 inches) and 13 of the products were too short (less than 5.0625 inches). In general, the difference between the measurement and ANSI tolerance was less than 0.25 inches, but some products were less than the minimum tolerance by up to 0.5425 inches. Although small differences are often not problematic, manufacturers should strive to meet the ANSI requirements to help ensure physical compatibility with luminaires.

## Other Characteristics

**Operating Environment**

PAR38 lamps are used in a variety of applications, including outdoors (e.g., residential security lighting). Typical halogen PAR38 lamps are sealed-beam and offer substantial weather resistance—note that they are not all rated for wet locations, however. In contrast, only one of the Series 20 LED PAR38 lamps (12-90) indicated that it was rated for operation in a wet location, and only in the base-up configuration. Many other lamps indicated that they were rated for damp locations, and could be used outdoors in a weather-protected fixture. Some indicated they were for use in dry or indoor locations only, and some provided no notice at all. Regardless of the claim, these notices were often included only in the fine print; consumers purchasing LED lamps for use outdoors may not understand that a given lamp is not appropriately rated and could fail prematurely.

Another important characteristic is whether a lamp can be used in a totally enclosed fixture. LED lamps use conduction and/or convection to move heat away from the LEDs. Improper thermal management, or use in an inappropriate environment, can affect an LED product's performance and/or cause it to fail prematurely. There are no such concerns with halogen lamps. Half of the Series 20 LED lamps provided an explicit warning against using the lamp in an enclosed fixture. In contrast, only four products (12-62, 12-65, 12-90, and 12-96) indicated they are suitable for use in enclosed fixtures. The remaining products did not provide any information on the subject.

**Dimming**

Although the dimmability of LED products is generally considered an advantage over other energy efficient alternatives like CFL and CMH, it is generally a liability compared to halogen. As a resistive load, halogen lamps dim smoothly from 100% to 0%, although audible noise may occur. In contrast, while many LED lamps are "dimmable"—only five of the Series 20 lamps were not available in a dimmable version—there are often limitations regarding the type of control hardware that can be used, or the dimming range. For example, the following is a selection of statements from the packaging of the Series 20 products:

- "Dimmable to 5% of light on most dimmers" (12-65)
- "Use only dimmers rated 600W or lower, made after 1995" (12-66)
- "Dimmable to 20% with ELV dimmers" (12-67)
- "Dimmable when using leading edge dimmers" (12-77)
- "Can only be dimmed. Do not use with timers or other control devices" (12-80)
- "10-100% - Not suitable for all dimmers" (12-93)
- "100% to 10% on most incandescent commercial dimmers" (12-96)
- "Compatible with most TRIAC dimmers" (12-99)

- "TRIAC dimmer 10%-100% (110V)" (12-100)
- "Dimming range 20-100%" (12-104)
- "Fully dimmable and can be used with the Lutron line of electronic low voltage dimmers" (12-135)

In short, it takes some investigation to ensure that an LED product will work with a given dimmer. Even if interoperability is possible, the dimming range and characteristics when dimming—color and flicker, for example—may not stack up to what is possible with halogen.

**Radiated Energy and Spectral Power Distribution**

LED lamps generally have a different spectral power distribution than conventional lamps, with more opportunity to add or subtract specific ranges of wavelengths, such as infrared (IR), ultraviolet (UV), or specific wavelength regions within the visible spectrum. This is an important attribute to consider when lighting sensitive objects, such as artwork. Similarly, limiting infrared (heat) in the radiated beam can be especially important when illuminating heat-sensitive objects, such as food (e.g., chocolate). White LEDs emit very little infrared radiation. In contrast, halogen lamps emit approximately 85% of the total input power as infrared radiation.

## Manufacturer Claims

Evaluating the accuracy of manufacturers' performance claims is an important component of the CALiPER program. This task is often difficult because different values are reported in different literature. For example, performance values listed on specification sheets are sometimes different from values listed by LED Lighting Facts or on product packaging. In some cases, these differences may be attributable to rounding to simplify visual appearance or improve legibility. In others, nominal values may be used instead of a single specific test result to better reflect the distribution of performance that can be expected from lighting products (i.e., not every product is identical). In other cases, updates to products may not be immediately reflected in literature. In total, 25 of the 38 Series 20 LED products had a listed performance value that varied by the data source or provided a nonspecific performance range. In comparing measured values to listed values, CALiPER uses data from specification sheets or product webpages first, then from product packaging, then from LED Lighting Facts if the other sources are not available.

Most of the Series 20 LED products had data available for all of the major performance criteria. Of the 37 products that listed a value, 26 were measured to be within ±10% of the listed lumen output,[10] whereas five products (12-62, 12-77, 12-80, 12-94, and 12-103) emitted more than 110% of the listed lumens and seven products (12-66, 12-76, 12-88, 12-96, 12-98, 12-100, and 12-102) emitted less than 90% of the rated lumens. The most under-performing product (12-66) was measured at 77% of the rated lumen output. Although producing more lumens than claimed—potentially resulting in glare—is probably less likely to lead to consumer or specifier dissatisfaction, the accuracy of manufacturer data is still a fundamental concern. One product (12-103) actually emitted 146% of the rated lumen output.

Nine products failed to meet the ±10% criterion for input power, all drawing less than 90% of the rated input power. In addition, eight products had a measured efficacy greater than 110% of the listed value, and three products had an efficacy less than 90% of the manufacturer's rating. Notably, 23 of 38 products met all three claims for input power, efficacy, and lumen output, whereas four products did not meet any claims. The other 11 products failed to meet one or two of the claims for those parameters. In general, lower input power and higher efficacy are favorable, but the accuracy of reported data is also important for building consumer

[10] The ±10% criterion is used by CALiPER and LED Lighting Facts for determining accuracy. This evaluation does not imply that conventional products meet this level of accuracy. Regardless, it is especially important for new technologies to perform as expected.

confidence. One interesting note is that claimed efficacy did not always match the quotient of rated lumen output and rated input power.

In general, the manufacturer claims for color quality metrics were accurate. Only one product (12-101) had a CCT with more than a 10% difference from the claimed value. More importantly, the measured value of 6307 K was also outside the ANSI-defined range for a 5500 K lamp, which was the claim of the manufacturer. No product had more than a 10% differences between claimed and measured CRI values. However, two products (12-76 and 12-101) with a claimed CRI of 82 had a measured CRI of 75, which may correspond to a noticeable reduction in performance. Notably, these two products had CCTs of 6404 K and 6307 K, respectively.

In contrast, only 16 of 35 products were measured to be within ±10% of the claimed beam angle. However, ANSI assigns a tolerance for nominal beam angles, acknowledging variability in the manufacturing process. Based on these tolerances, only six of the Series 20 products failed to meet the manufacturer claim, as shown in Figure 9. Four of those six products had a measured value less than the manufacturer claimed. A similar story occurred with CBCP, where 8 of 26 products that made a claim failed to be within ±10%—three were under and five were over.

**Equivalency Claims**

Especially for those having less experience with and knowledge of lighting metrics, equivalency claims may be a key factor for purchasing. Of the 38 products tested for this report, 31 made claims of equivalency to a specified wattage and type of lamp—typically halogen. LED Lighting Facts uses lumen output to evaluate these claims, stating that an LED lamp must have a lumen output at least ten times greater than the input power of the claimed equivalent lamp (e.g., 750 lumens for equivalence to a 75 W halogen PAR38 lamp). Of the 31 products making a claim, 14 did not meet the LED Lighting Facts criterion. Instead of lumen output, ENERGY STAR relies upon CBCP to evaluate equivalency claims. Similarly, 13 of 31 products making a claim of equivalency failed to meet the minimum CBCP requirement using the ENERGY STAR CBCP tool. Notably, only nine products were considered to have misleading claims according to both evaluation methods. The general inaccuracy of equivalency claims—fewer than 60% of total claims were accurate using either evaluation method—is a cause for concern.

**LED Lighting Facts Products**

LED Lighting Facts lists products that are tested according to industry standards—the same standards that are used by CALiPER. Of the 38 Series 20 LED PAR38 lamps, 21 were listed by LED Lighting Facts, although only 12 indicated so on the specification sheet, webpage, or packaging. At least one product that was not listed had information about LED Lighting Facts on its specification sheet, which could be misleading to consumers. Of the 21 products listed by LED Lighting Facts:

- Seven (33%) were outside the ±10% criterion for lumen output. This is comparable to the 30% rate for the total group, but higher than the rate for products not listed by LED Lighting Facts (25%).
- Five (24%) were outside the ±10% criterion for input power. This is same as the rate for the total group and for products not listed by LED Lighting Facts.
- Six (29%) were outside the ±10% criterion for luminous efficacy. This is comparable to the 30% rate for the total group and for products not listed by LED Lighting Facts (31%).

These statistics suggest that PAR38 lamps listed by LED Lighting Facts are no more likely to meet manufacturer claims than products not listed by LED Lighting Facts. It is difficult to understand the root cause of this, given that products listed by LED Lighting Facts are tested in the same way as those included in the CALiPER program—although the CALiPER products are anonymously purchased. Further, there is no obvious trend toward overperforming or underperforming. One possible contributing factor is lamp-to-lamp variability, although the difference between CALiPER samples is generally small. Only two of the Series 20 products had more than a 10% difference in measured lumen output between the two samples, and the average overall difference was 0.4%.

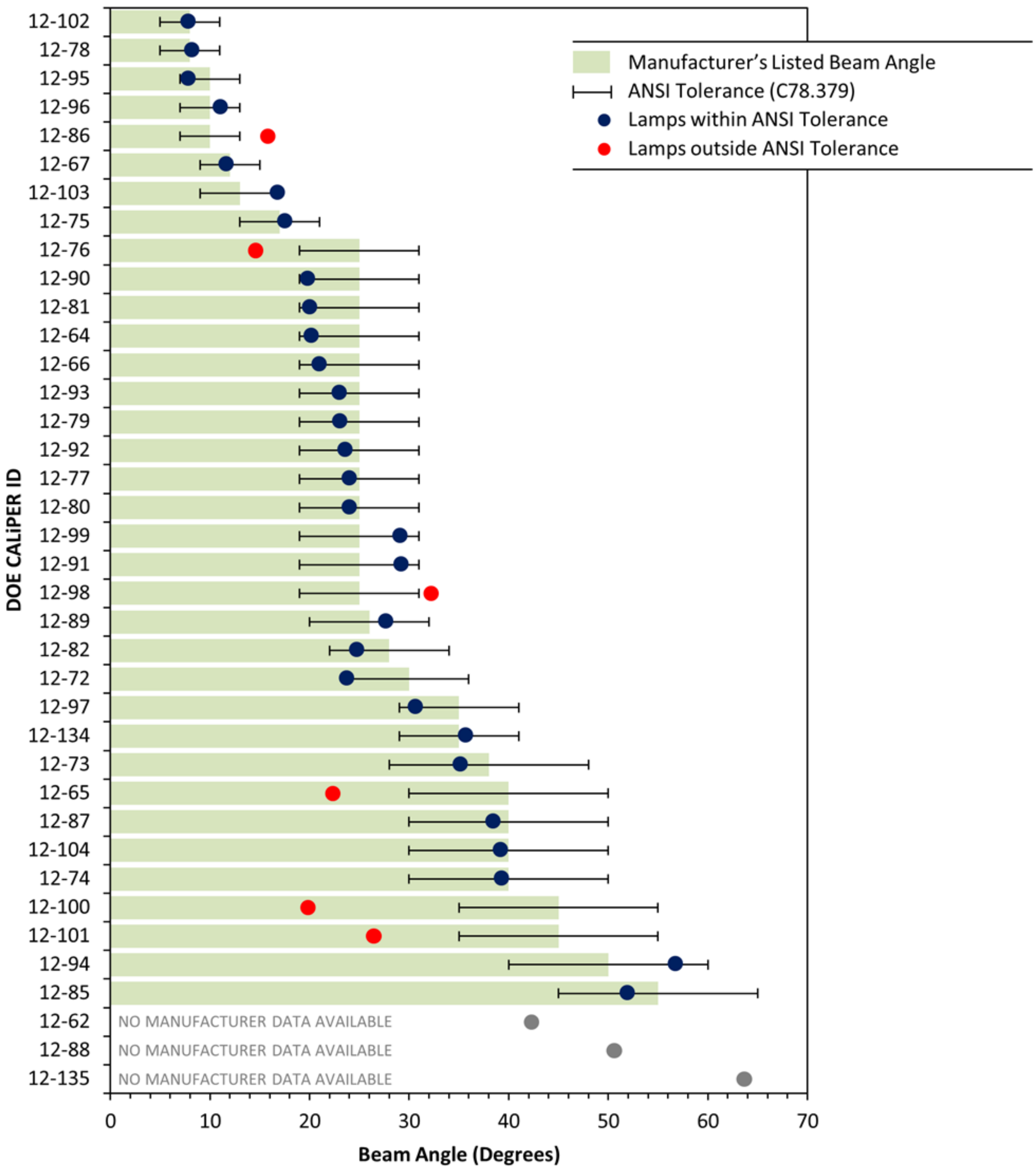



**Figure 9. Accuracy of manufacturers' claimed beam angle.** Six products fell outside ANSI tolerances.

Interestingly, eight products listed a different value on the specification sheet than what was listed by LED Lighting Facts. In most cases, however, the differences were small and could be attributed to rounding or simplifying written literature. Using the values listed by LED Lighting Facts to evaluate manufacturer claims, instead of specification sheets, would not have yielded different results.

One other noteworthy observation is that of the 13 products listed by LED Lighting Facts that were also ENERGY STAR qualified, only two were indicated as such in the LED Lighting Facts database. It is probable that products are being listed by LED Lighting Facts before ENERGY STAR testing is complete, and that the records are not updated by the manufacturer after qualification has been achieved.

**ENERGY STAR Products**
Slightly fewer products (18 of 38) were ENERGY STAR qualified than were listed by LED Lighting Facts. Of the 18 products:

- Three (17%) were outside the ±10% criterion for lumen output, with only one underperforming.
- One (6%) was outside the ±10% criterion for input power.
- Four (22%) were outside the ±10% criterion for luminous efficacy. Notably, one of these products was actually measured to be below the ENERGY STAR criterion of 45 lm/W.
- Five (28%) made an inaccurate equivalency claim, based on the measured data. However, four of those products had a measured CBCP within 10% of the minimum requirement of ENERGY STAR.

In summary, it appears ENERGY STAR qualified products are more likely to perform as claimed than the rest of the sample. Yet, some claims were still deemed inaccurate.

At least two products used the ENERGY STAR logo on manufacturer literature in a way that might lead a reader to believe the product was ENERGY STAR qualified, despite the fact that neither product was found on the ENERGY STAR list.

# 6 Conclusions

As tested by CALiPER, the Series 20 LED PAR38 lamps showed noteworthy promise for replacing up to 90 W halogen PAR38 lamps. Compared to earlier testing of products purchased between 2008 and 2010, the Series 20 lamps provided more lumen output, higher efficacy, and a more diverse selection of luminous intensity distributions. Further, the efficacy and color characteristics are similar to or better than directional CFL and CMH lamps, yet LED lamps offer more variety and better operating characteristics, such as instant-on performance. Adding other factors such as dimmability and longer rated lifetime makes LED PAR38 lamps the best solution for replacing inefficient PAR38 lamps, many of which are now effectively outlawed by federal regulations.

The performance of the Series 20 products can be summarized as follows:

- The lumen output of the majority of the products was approximately equivalent to 60 W halogen PAR38 lamps, although some were as low as 40 W or as high as 90 W halogen PAR38 lamps.
- Excluding one product with very low efficacy (26 lm/W), the Series 20 products had luminous efficacies between 44 and 79 lm/W. A majority of products had an efficacy between 50 and 60 lm/W, and the average for the group was 56 lm/W. This is favorable compared to other light source types commonly used in directional lamps, and should continue to rise.
- The Series 20 LED PAR38 lamps had luminous intensity distributions ranging from very narrow (8° beam angle) to very wide (64° beam angle). The suitability of these distributions depends on the application, but the range covers what is available from halogen PAR38 lamps.
- Although there were a few exceptions—two products had a CCT above 5000 K, and three products had a CRI less than 80—most of the Series 20 lamps had color quality attributes appropriate for replacing conventional PAR lamps in most applications. Some applications, such as museums, may require better color rendering, which would limit the number of available LED options.
- The power factor of the Series 20 lamps was considerably better than previously tested LED PAR38 lamps, with all but one of the products exceeding the ENERGY STAR minimum requirement of 0.70.
- Many of the manufacturer claims were accurate; however, there was a tendency for the lamps to exhibit higher efficacies and draw less power than reported in the manufacturers' literature. A number of products also emitted fewer than 90% of claimed lumens, and the measured beam angle for six products was outside the tolerance established by ANSI.

Although the results from this series of testing were encouraging, there is room for LED PAR38 lamps to improve and gain a larger market share. Many of the products tested for this report had more than one option for beam angle and color temperature, but products available in multiple lumen packages were less prevalent. Another current concern is cost; on average ($70.58), the Series 20 LED PAR38 lamps were several times more expensive than halogen PAR38 lamps.

With one or two possible exceptions, all of the lamps in Series 20 were appropriately designated as PAR lamps. A similar conclusion was reached in CALiPER Report 16 for LED BR30/R30 lamps, although there were a few products that would be more appropriately labeled as PAR lamps. Thus, it appears that most manufacturers are effectively designating lamps based on the similarity in performance to the conventional counterpart.

CALiPER plans to conduct additional testing on the Series 20 LED PAR38 lamps to investigate performance attributes that are not captured by LM-79 testing. These results will be published in subsequent reports.

# Appendix A: Definitions

| | |
|---|---|
| **Beam Angle**<br>Degrees (°) | The angle between the two directions for which the intensity is 50% of the maximum intensity (ANSI/IES RP-16-10) or center beam intensity (ANSI C78.379-2006), as measured in a plane through the beam axis. For example, if the maximum intensity is 1000 cd, the angle at which the intensity is 500 cd is half of the beam angle. If 500 cd occurs at 20° from center beam, then the beam angle is 40°. |
| **Center Beam Candlepower (CBCP)**<br>Candela (cd) | The luminous intensity at the central axis of the beam, which typically corresponds to a vertical angle of 0° (called nadir for lamps oriented downward). Although candlepower is a deprecated term, it is still widely used in this context. |
| **Correlated Color Temperature (CCT)**<br>Kelvin (K) | The absolute temperature of a blackbody radiator having a chromaticity that most nearly resembles that of the light source. CCT is used to describe the color appearance of the emitted light. |
| **Color Rendering Index (CRI or $R_a$)** | A measure of color fidelity that characterizes the general similarity in color appearance of objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for a sample of eight color samples illuminated with the test and reference source. See also: *Special Color Rendering Index $R_9$.* |
| **$D_{uv}$** | The distance from the Planckian locus on the CIE 1960 UCS chromaticity diagram (also known as u', 2/3 v'). A positive value indicates the measured chromaticity is above the locus (appearing slightly green) and a negative value indicates the measured chromaticity is below the locus (appearing slightly pink). The American National Standards Institute provides limits for $D_{uv}$ for nominally white light. |
| **Field Angle**<br>Degrees (°) | The angle between the two directions for which the intensity is 10% of the maximum intensity (ANSI/IES RP-16-10) or center beam intensity (ANSI C78.379-2006), as measured in a plane through the beam axis. For example, if the CBCP is 1000 cd, the angle at which the intensity is 100 cd is half of the field angle. If 100 cd occurs at 32° from center beam, then the field angle is 64°. |
| **Input Power**<br>Watts (W) | The power required to operate a device (e.g., a lamp or a luminaire), including any auxiliary electronic components (e.g., ballast or driver). |
| **Luminous Efficacy**<br>Lumens per watt (lm/W) | The quotient of the total luminous flux emitted and the total input power. |
| **Luminous Intensity Distribution**<br>Candela (cd) | The directionality of radiant energy emitted by a source, which may be shown using one of several techniques. It is most often presented as a polar plot of the candelas emitted in a vertical plane through the center of the lamp or luminaire. |
| **Output**<br>Lumens (lm) | The amount of light emitted by a lamp or luminaire. The radiant energy is weighted with the photopic luminous efficiency function, V(λ). |
| **Power Factor** | The quotient of real power (watts) flowing to the load (e.g., lamp or fixture) and the apparent power (volt-amperes) in the circuit. Power factor is expressed as a number between 0 and 1, with higher values being more desirable. |

**Special Color Rendering Index $R_9$**

A measure of color fidelity that characterizes the similarity in color appearance of deep red objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for the color sample illuminated with the test and reference source. $R_9$ and $R_a$ (CRI) are part of the same CIE Test-Color Method, but the $R_9$ color sample is not included in calculation of $R_a$. $R_9$ values should not be compared to $R_a$ (CRI) values. As a shorthand approximation, an $R_9$ less than zero is poor, an $R_9$ greater than zero is good, an $R_9$ greater than 50 is very good, and an $R_9$ greater than 75 is excellent.

## Appendix B: Product Selection

Product selection is an important part of the CALiPER process. Products are selected with the intent of capturing the current state of the market—a cross section ranging from expected low to high performing products with the bulk characterizing the middle of the range. However, the selection does not represent a statistical sample of all available products.

Product selection starts with a review of the technology. Beyond relying on professional experience, the team surveys:

- Trade publications, including *Lighting Design + Application*, *LEDs Magazine*, *Mondo ARC*, and *Architectural Lighting*
- Internet websites, including Elumit, DesignLights Consortium, ENERGY STAR, LED Lighting Facts, ESource, and Lightsearch
- National retailers, including Grainger, Goodmart, The Home Depot, Lowe's, Amazon, and Sears
- Other sources, including trade shows (local and national) and manufacturers' representatives

After surveying available products, the CALiPER team characterizes the features of the products and determines what can be standardized to ease comparison. For this report focusing on LED PAR38 lamps, the following features were evaluated and led to the final selection:

- Lumen package – Products making equivalency claims to incandescent or halogen lamps drawing 75 W or more, or exceeding 1,000 lumens, were targeted.
- Luminous intensity distribution – The goal was to test lamps spanning the range of beam angles found with halogen PAR38 lamps. If a product was available with a spot distribution (less than 20° beam angle), it was given preference. Many LED lamps with a 25° beam angle were available.
- Color temperature – In general, a CCT of 3000 K was chosen if available, although some lamps at 2700 K or with higher CCTs also made the final list.
- Color rendition – Lamps with a high CRI were sought. All of the lamps were listed as having a CRI above 80 by the manufacturer.
- Lamp diameter/shape – Most importantly, the manufacturer literature (including websites) had to indicate that the lamp was a PAR38 replacement.

Other non-performance related criteria are also considered:

- Product availability – As a federally funded program, CALiPER focuses on products available in the United States.
- Energy efficiency programs – Some emphasis is given to including products listed by large energy efficiency programs (e.g., ENERGY STAR).

After establishing a list of appropriate products, attempts are made to anonymously purchase the products through standard industry resources (e.g., distributors, retailers). Sometimes, products are not available or cannot be shipped in a timely manner. Thus, the final group of products tested does not always match the intended results of the selection process.

# Appendix C: Previous CALiPER Testing of LED PAR38 Lamps

**Table C1. Summary data for previous CALiPER tests of LED PAR38 lamps.** The first two digits of the CALiPER Test ID indicate the year in which the product was purchased.

| DOE CALiPER Test ID | Initial Output (lm) | Total Input Power (W) | Efficacy (lm/W) | Power Factor | CRI | CCT (K) | $D_{uv}$ | CBCP (cd) | Beam Angle (deg) | Field Angle (deg) |
|---|---|---|---|---|---|---|---|---|---|---|
| 08-15 | 323 | 13.4 | 24 | 0.46 | 67 | 3127 | 0.0018 | 922 | 55 | 143 |
| 08-131 | 315 | 11.3 | 28 | 0.58 | 93 | 2953 | -0.0049 | 459 | 38 | 85 |
| 09-30 | 632 | 14.6 | 43 | 0.55 | 83 | 2924 | 0.0011 | 1,094 | 41 | 71 |
| 09-63 | 289 | 5.0 | 58 | 0.42 | 72 | 6177 | -0.0034 | 902 | 22 | 51 |
| 09-94 | 635 | 15.6 | 41 | 0.85 | 84 | 3070 | -0.0027 | 3,199 | 20 | 43 |
| 10-04 | 565 | 11.2 | 50 | 0.94 | 93 | 2667 | -0.0018 | 4,465 | 18 | 34 |
| 10-11 | 705 | 17.0 | 42 | 0.98 | 82 | 2759 | -0.0013 | 7,528 | 13 | 26 |
| 10-29 | 959 | 18.4 | 52 | 0.75 | 87 | 4056 | 0.0030 | 3,684 | 25 | 47 |
| **Minimum** | 289 | 5.0 | 24 | 0.42 | 67 | 2667 | - | 459 | 13 | 26 |
| **Mean** | 553 | 13.3 | 42 | 0.69 | 83 | 3466 | - | 2,782 | 29 | 67 |
| **Maximum** | 959 | 18.4 | 58 | 0.98 | 93 | 6177 | - | 7,528 | 55 | 143 |

# Appendix D: CALiPER Testing of Conventional PAR38 Lamps

**Table D1. Summary data for CALiPER tests of benchmark conventional PAR38 lamps.** The first two digits of the CALiPER test ID indicate the year in which the product was purchased.

| DOE CALiPER Test ID | Source Type | Initial Output (lm) | Total Input Power (W) | Efficacy (lm/W) | Power Factor | CRI | CCT (K) | CBCP (cd) | Beam Angle (deg) | Field Angle (deg) |
|---|---|---|---|---|---|---|---|---|---|---|
| BK12-68 | Halogen-IR | 933 | 62.0 | 15 | 1.00 | 99 | 2842 | 2,590 | 30 | 47 |
| BK12-69 | Halogen | 1,073 | 75.3 | 14 | 1.00 | 99 | 2887 | 15,360 | 11 | 22 |
| BK12-70 | Halogen | 1,013 | 74.9 | 14 | 1.00 | 99 | 2858 | 4,347 | 21 | 43 |
| BK12-71 | Halogen | 1,036 | 76.1 | 14 | 1.00 | 99 | 2867 | 15,060 | 10 | 21 |
| BK08-05 | Halogen | 524 | 46.2 | 11 | 1.00 | 99 | 2720 | 2,517 | 22 | 37 |
| BK12-63 | CFL | 1,144 | 22.4 | 51 | 0.61 | 83 | 2699 | 461 | 87 | 180 |
| BK09-111 | CMH | 1,504 | 25.2 | 60 | 0.96 | 86 | 3012 | 5,162 | 26 | 38 |
| **Minimum** | | 524 | 22.4 | 11 | 0.61 | 83 | 2699 | 461 | 10 | 21 |
| **Mean** | | 1,032 | 54.6 | 25 | 0.94 | 95 | 2840 | 6,500 | 29 | 55 |
| **Maximum** | | 1,504 | 76.1 | 60 | 1.00 | 99 | 3012 | 15,360 | 87 | 180 |

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